Design of A High Charge (10 - 100 nC) and Short Pulse (2 - 5 ps) RF Photocathode Gun for Wakefield Acceleration

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Abstract: In this paper we present a design report on a 1-1/2 cell, L Band RF photocathode gun that is capable of generating and accelerating electron beams with peak currents > 10 kA. We have performed simulation for bunch intensities in the range of 10 - 100 nC with peak axial electrical field at the photocathode of 30 - 100 MV/m. Unlike conventional short electron pulse generation, this design does not require magnetic pulse compression. Based on numerical simulations using SUPERFISH and PARMELA, this design will produce 20 - 100 nC beam at 18 MeV with rms bunch length 0.6 -1.25 mm and normalized transverse emittance 30 - 108 mm mrad. Applications of this beam for wakefield acceleration is also discussed.

Introduction

High current short electron beams have been a subject of intensive studies [1]. One of the particular uses for this type of beam is for wakefield acceleration applications. In the case of the plasma wakefield acceleration scheme[2], the excited wakefield amplitude not only depends on the drive beam charge but is also very sensitive to the pulse length. This is particularly true in the case of nonlinear plasma wakefields in the blow out regime, because the plasma wave breaking limit is proportional to the beam density. In general, the drive pulse length (FWHM) should not exceed 1/3 of the excited wake field wavelength for optimal coupling of the beam energy to the wakefield. Dielectric structure based wakefield acceleration research has concentrated on structures in the 10 - 20 GHz range, but in order to study high gradient wakefield acceleration in high frequency 30 GHz structures, high charge (> 20 nC) and short (< 10 ps FWHM) electron beam is required.

High current (kA) short electron beam generation and acceleration did not materialize until the invention of RF photoinjector technology[3]. Although most RF photocathode has been concentrated on high brightness, low charge applications such as free electron laser injectors, there have been several relatively high charge rf photocathode based electron sources built and operated[4,5,6]. In general, there are two approaches to attaining high peak current. One approach is to generate an initially long electron bunch with a linear head-tail energy variation that is subsequently compressed using magnetic pulse compression. The advantage of magnetic compression is that it is a well-known technology and can produce sub-picosecond bunch lengths. Due to the strong longitudinal space charge effects, this technology is limited to somewhat lower charges (<10 nC). There have also been designs and operations of relatively high charge L-band guns at APEX[5] and TTF[6]. Another approach is to directly generate short intense electron bunches at the photocathode and then accelerates them to relativistic energies rapidly using high

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peak axial electric fields in the gun [4]. The advantage of this approach is that it can deliver very high charges, for example, 100 nC if one uses an L-band gun. This would satisfy the requirements of most electron driven wakefield experiments for both plasma and dielectric structures if the pulse length is short enough (< 10 ps FWHM). So far, the Argonne Wakefield Accelerator (AWA) has demonstrated the capability of producing 100 nC, 25 — 35 ps (FWHM) electron beams at 14 MeV. This unprecedented performance was obtained using a half cell photocathode gun cavity and two standing wave iris-loaded linac sections [7]. The AWA machine has reached its design goal and has been used for dielectric wakefield [8] and plasma [9] experiments. The initial results are encouraging [10]. Achieving higher gradients in wakefield experiments would require the drive electron pulse to be even shorter and have a lower emittance. In this paper, we discuss a new design for the RF photocathode gun with the capability of producing 10 - 100 nC with 2 - 5 ps (rms) pulse lengths.

Design Approaches

The physics of high current beam generation and transport is very complicated and some analytical work has been performed[11, 12]. In general pulse lengthening is due to space charge effects, particularly in the high charge case. One can simply estimate the longitudinal space charge force of a 100 nC beam with 1 cm radius in the rest frame as 27 MV/m. Another effect is the transverse rf focusing and defocusing of the electron beam passing through the accelerating cavity, which causes both pulse lengthening and transverse emittance growth. Therefore, one needs to accelerate the electron beams generated from the cathode as fast as possible (high gradient) and to be relativistic before exiting out the RF gun. Thus in this new design, we took a brute force approach: 1) the electron beam is born in a strong axial electric field; 2) the beam is continuously accelerated with gradient as high as possible, therefore preventing bunch lengthening and emittance growth. 3) Adjusting an external focusing solenoid to minimize the emittance, eventually approaching the so called " emittance compensated" beams.

The choice for our new gun design is a Brookhaven type [13] 1— 1/2 cell cavity scaled up to L band operation as shown in Figure 1. Although in general the beam will have lower emittance if one chooses a multi-cell gun cavity, RF power requirements will be excessive. In this study, the updated standard computer codes from Los Alamos SUPERFISH and PARMELA [14] are used to model cavity fields and beam dynamics respectively.

Figure 1 shows a schematic diagram of the new gun and a section of the Linac. The linac section used here is an existing section from the current AWA linac[15]. The drift distance between the gun and the linac is 32.3 cm designed to permit laser input and beam diagnostics. The following table summarizes the parameters used in our simulation of the new rf gun.

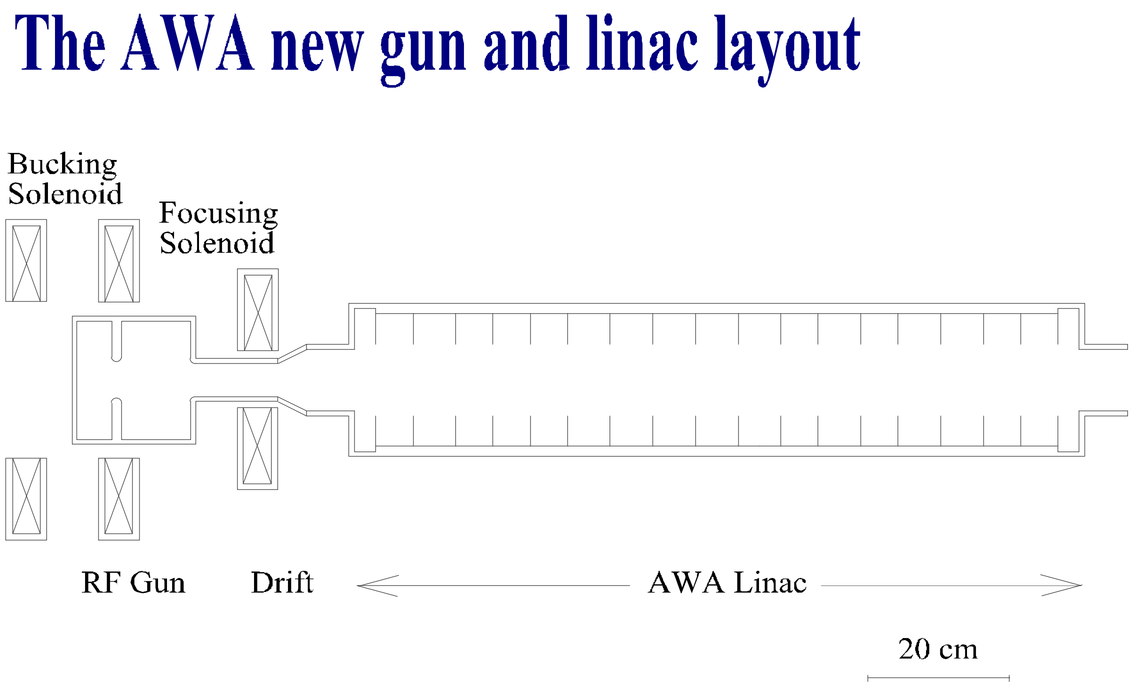

Figure 1. Schematic layout of the proposed AWA new electron gun and a section of the existing linac section.

Table 1 The gun design parameters as calculated using SUPERFISH

Inner Radius of the Cell, b (cm)	9.03
Radius of the iris, a (cm)	2.75
Width of the iris, d (cm)	1.5
Aperture of the exit (cm)	2.5
Operating frequency (GHz)	1.3
Initial bunch length (ps)	8.5
Initial beam radius (cm)	1
Quality factor, Q	26008
Shunt impedance (MΩ/m)	36.47

Numerical simulation results

Low Charge cases (10 - 40 nC)

As described in the above sections, for wakefield acceleration applications, one needs electron beam with charges in the range of 10 - 40 nC; also pulse length needs to be as short as 2 ps. In order to achieve such a number, we have systematically studied the optimized beam parameters for 10, 20, and 40 nC.

The simulation is done using the rf gun cavity parameters in table 1. We assume 1 cm laser radius at the photocathode with a flat top distribution. The laser pulse length used here are 2.6 ps for 10 nC, 5.2 ps for 20 nC and 10.4 ps for 40 nC beams. The choice of the laser pulse length is determined by the current AWA laser system The dependence of the electron beam rms emittance and pulse length is studied as a function of the axial electrical field on the photocathode with optimization done by varying the launch phase and gun solenoid field.

Figure 2 shows the dependence of the rms emittance and pulse length on the axial electrical field on the cathode. One can see that both quantities decrease drastically as the axial electrical field increases. At 80 MV/m, the rms emittance is 30 mm -- mrad and a pulse length of 0.33 mm is obtained. Even at 50 MV/m, σ is 0.6 mm and ε is 60 mm -- mrad. These results are much improved over the current AWA beam parameters at the same charge [7].

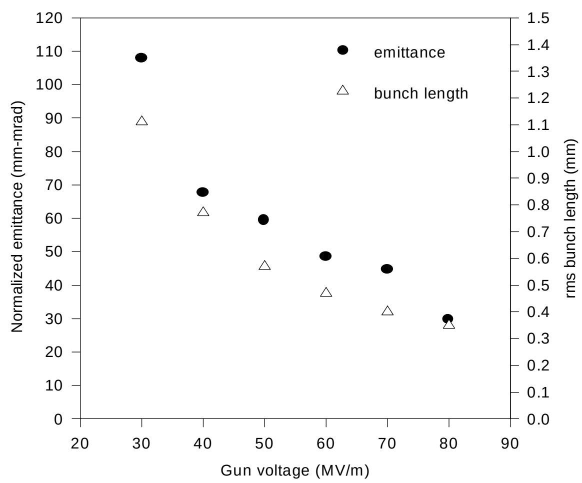

Figure 2. Dependence of the beam parameters at the linac exit on gun axial electrical field. For a 10 nC beam, one can obtain very short and low emittance bunches even at relatively low axial electric field.

The simulation results for the 20 nC and 40 nC cases are similar to the 10 nC, although both pulse length and emittance are increased due to space charge effects and also longer initial laser pulses. Figure 3 shows the dependence of pulse length and emittance as a function of the axial electrical field on the cathode for the 40 nC case. At 80 MV/m, σ_z of 1.1 mm for 40 nC can be achieved. This is much better than the existing AWA gun which has rms pulse length of 5 mm at this intensity. We should point out that one should be able to obtain reasonable performance even at 60 MV/m cathode field. This field strength has already been achieved at the current 1/2 cell AWA drive gun.

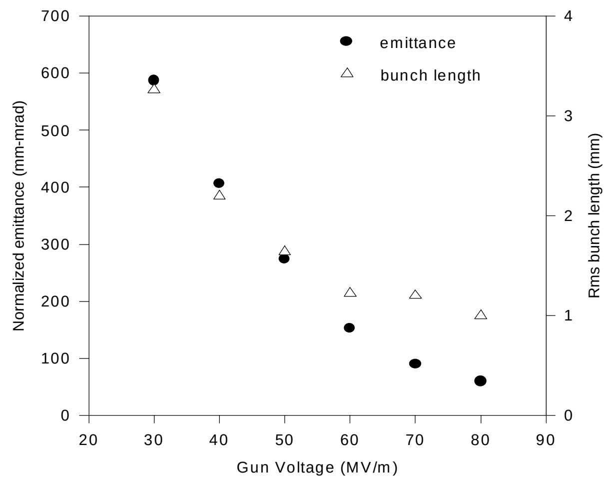

Figure 3. Dependence of the beam parameters on gun axial electrical field at the exit of linac for 40 nC beam intensity.

High charge cases (100 nC)

In this section, we describe the simulation results for 100 nC beam charge. We assume 1 cm laser radius at the photocathode with a flat top distribution. The laser pulse length in all simulations is 8.5 ps also assuming a flat top distribution. The simulation parameters were varied systematically to optimize the final bunch length and emittance. We scan through solenoid field strength and rf injection phase and fields strength at cathode from 50 -110 MV/m. Our criteria for selecting the operating point is combination of parameters which gives the shortest pulse and lowest emittance.

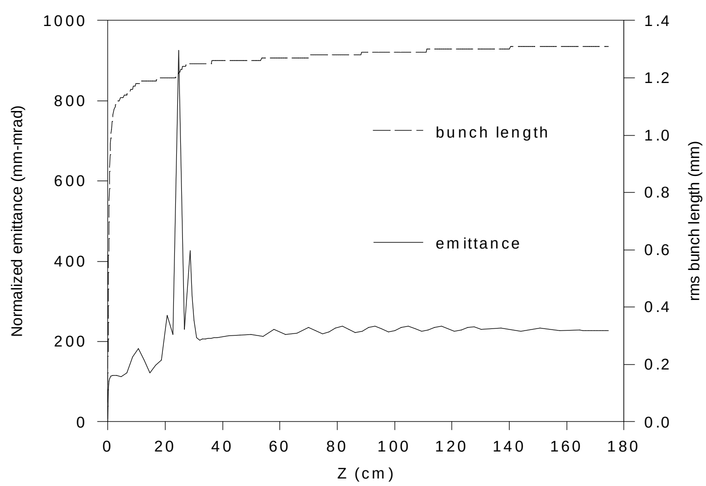

Figure 4. 100 nC beam rms bunch length and emittance evolution in the gun and linac for an optimized parameters.

Figure 4 shows a 100 nC bunch length and emittance evolution in the gun and linac for an optimized parameters. The effect of the peak electric field in the gun on the rms bunch length and emittance for an 100 nC beam is much stronger than at lower intensities. As expected, both emittance and pulse length decreases as the electric field increases. At 100 MV/m surface field along with axial solenoid magnetic field of 2 kG, and rf injection phase of 33°, one can achieve σ_Z = 1.3 mm (4 ps) and normalized emittance ε_N = 108 mm mrad (90% as defined in PARMELA) at the end of the linac with no beam losses. This is a very interesting result because it approaches the ~ 1 mm mrad/ nC attainable in so called "emittance compensated" beams. This is a significant improvement over the existing AWA gun design (σ_z = 4 mm, and ε_N=800 mm mrad). Figure 5 shows the beam's energy dependence on the cathode fields with energy range from 5 MeV - 11 MeV and energy spread of typically < 3 %. However, because PARMELA does not include wakefield or beam loading in its calculations, the energy spread can be much higher, particularly in the high charge cases. Typically it adds another 5% for AWA gun at 100 nC[15].

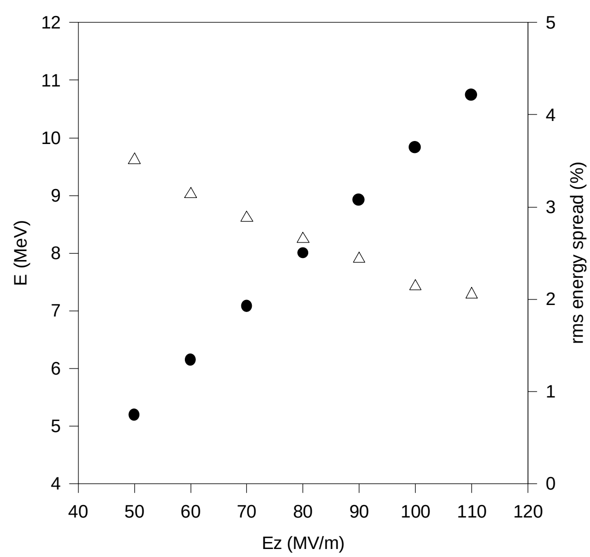

Figure 5. Output energy and energy spread dependence on the cathode field. Solid dots are energy and triangles are energy spread.

We would like to point out that for the 100 nC beam, the axial electrical field on the photocathode has to be greater than 70 MV/m. Also due to the intense radial space charge forces and higher energy of the beam, a strong solenoid field ~ 2 kG has to be maintained. This field strength is very high for this type of solenoid design.

Discussion and Summary

In the last section we showed that the 1 - 1/2 cell rf photocathode gun plus a section of the current AWA linac would yield a very low emittance and can be attained with a short electron beam. For a 20 nC electron beam, rms pulse length of 0.7mm is observed and 22 mm mrad normalized emittance with energy of 18 MeV. If this beam is used as a plasma wakefield accelerator driver, it can excite gradient in excess of 1 GeV/m with a plasma density of ~10^{14} /cm^3 [16].

In applications to dielectric wakefield acceleration, this beam would also make a significant improvement over present attainable gradients. One can use this beam to directly demonstrate collinear wakefield acceleration gradients in excess of 50MV/m corresponding to 200 MW rf power generated in 30 GHz dielectric structures.

We have designed an RF photocathode gun for high current applications. The numerical simulation results indicate that 10 kA peak current can be obtained. This beam will enable us to study high gradient wakefield acceleration in both plasma and dielectric wakefield accelerator..

This work is supported by the Department of Energy, High Energy Physics Division, Advanced Technology Branch under the Contract No. W-31-109-ENG-38.

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